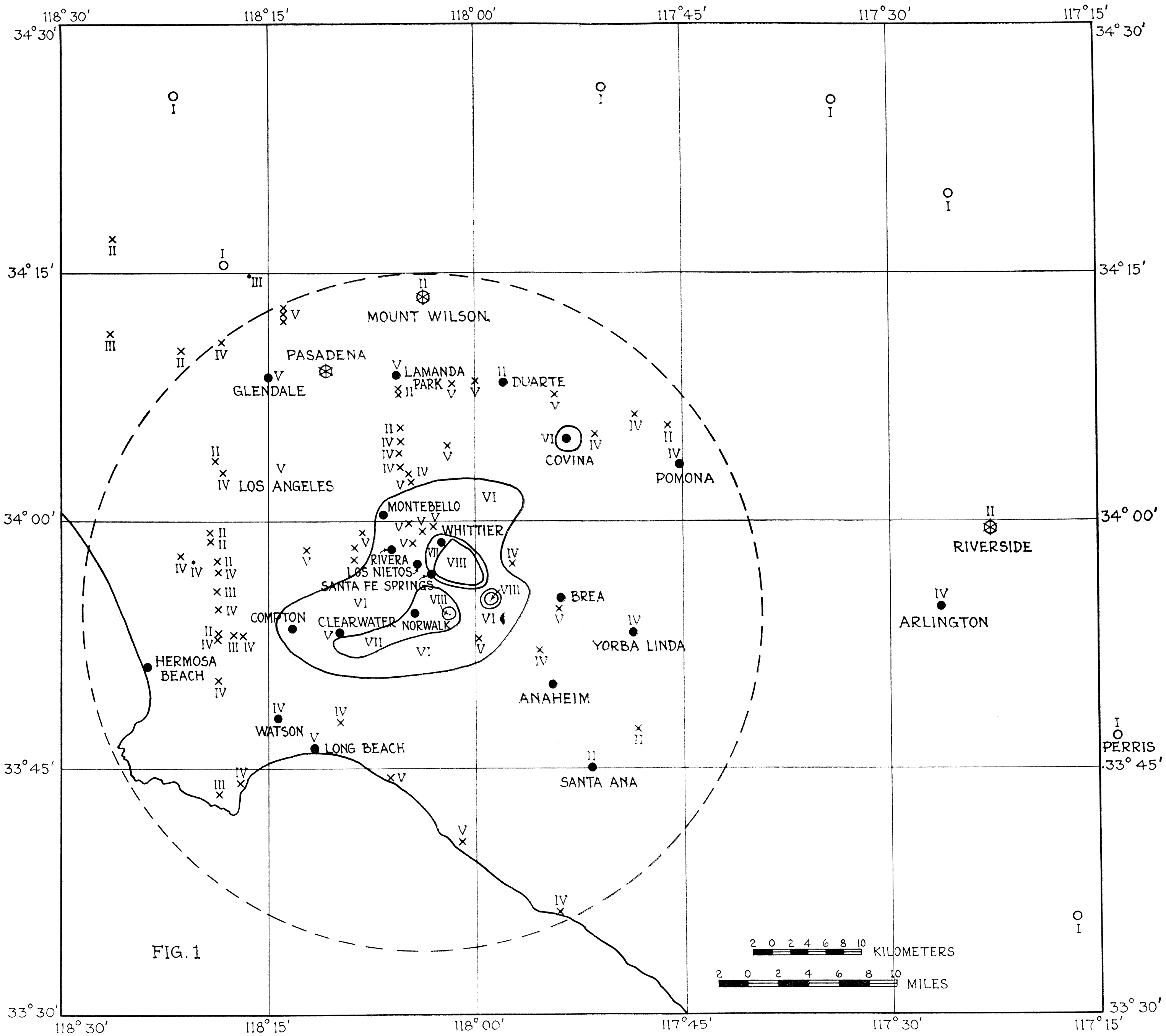
MOUNT WILSON
PASADENA
GLENDALE
LAMANDA PARK
DUARTE
COVINA
POMONA
LOS ANGELES
MONTEBELLO
WHITTIER
RIVERA
LOS NIETOS
SANTA FE SPRINGS
COMPTON
CLEARWATER
NORWALK
BREA
YORBA LINDA
ANAHEIM
HERMOSA BEACH
WATSON
LONG BEACH
SANTA ANA
RIVERSIDE
ARLINGTON
PERRIS
KILOMETERS
MILES
FIG. 1

Fig. 1

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RECENT EARTHQUAKES NEAR WHITTIER, CALIFORNIA

BY HARRY O. WOOD AND CHARLES F. RICHTER

This paper deals with recent earthquakes noted in a small area near and to the south of Whittier, California, culminating in a shock at 8:46 a.m., P.S.T., on July 8, 1929, which just barely attained destructive intensity. Since the establishment of the Seismological Laboratory and the first group of auxiliary stations of the co-ordinated network in southern California, installed in 1926 and 1927, earthquakes emanating from this district have been registered as follows: a sharp shock at 11:14 a.m., P.S.T., on October 8, 1927; a swarm of small shocks on December 30 and 31, 1928; and a group in May, 1929. Also, following the main shock, many aftershocks occurred within a few hours, and since then shocks have continued to occur, at increasingly long and irregular intervals, down to the time of writing.

Also, in recent years other earlier shocks have originated in or near this district, which may be related genetically to those of the series chiefly under consideration here. Some of these occurred before routine registration was begun at any of the auxiliary stations of the network. Such shocks are listed immediately below.

A shock occurred at about 12:57 p.m., P.S.T., on December 6, 1923, which was felt throughout the area of the Los Angeles plain. This probably was centered roughly to the south of Whittier. No damage of consequence resulted, although it was reported that an oil derrick at the Santa Fe Springs oil field was "wrecked" (more probably "damaged").

A slight shock, attaining intensity IV Rossi-Forel, or more, occurred at about 7:47 p.m., P.S.T., on January 2, 1924. This was felt distinctly in and near Whittier, and in Los Angeles, Pasadena, and neighboring places also.

A slight tremor was felt at Whittier at about 7:57 a.m., P.S.T., on May 7, 1924.

In November, 1926, several shocks were felt in this district: one was reported on November 4th at about 2:38 p.m., P.S.T., from Yorba Linda (see frontispiece), where the intensity was about IV, and from Anaheim and neighboring points also; another, which also attained an intensity of about IV at Yorba Linda, was felt at Santa Ana also and at other neighboring places at about 11:47 a.m., P.S.T., on November 7th; still other shocks were reported later during the same day. Several shocks were felt in Santa Ana and nearby places during the evening of November 8th and the morning and forenoon of November 9th; of these, seven were registered at the auxiliary station at Riverside. A slightly stronger shock, at about 9:23 a.m., P.S.T., on November 9th, was felt at Anaheim and Santa Ana, and at Yorba Linda also, where the intensity reached grade V of the Rossi-Forel scale. One further shock was reported felt at Yorba Linda at about 10:10 a.m., P.S.T., on November 11th, but this was not registered by the seismographs. These November shocks manifested no marked intensity in the immediate vicinity of the Whittier district. Instrumental records at Pasadena and Riverside indicate an origin to the eastward of that under discussion below.

The earthquake at 11:14 a.m., on October 8, 1927, was a sharp shock of very brief duration, resembling the impact of an explosion as experienced at Pasadena and Los Angeles. Until information was received from other scattered points situated at considerable distances from each other it was considered that the shock was probably due to an explosion or a heavy blast. Its intensity may have reached VI Rossi-Forel at Glendale, where plate glass windows were reported broken, but elsewhere there was no indication of so high a value. This, therefore, may have been an anomalous effect. On this occasion the instrumental records at Pasadena were defective, but the seismograms from Riverside, Santa Barbara, and La Jolla indicated an origin near to the source of the shocks discussed below. The shock was felt as far as Pomona, and perhaps at Riverside.

A swarm consisting of twenty-eight earthquakes was recorded at Pasadena on December 30 and 31, 1928. Of these the strongest occurred at about 2:45 a.m., P.S.T., on the 31st. This was felt at Compton, where the intensity reached a value of about V Rossi-Forel, and, apparently with less intensity, throughout the area of the Los Angeles plain. At Long Beach it was reported brief in duration, resembling an explosion. The $S-P$ intervals measured were 3.2 seconds at Pasadena, 4.5 seconds at Mount Wilson, 8.8 seconds at Riverside, and 19.2 seconds at Santa Barbara. These indicate an origin not far to the east of Compton. This will be discussed more fully later.

An earthquake at 5:07 p.m., P.S.T., on May 4, 1929, was felt generally in the Whittier district. This was followed by shocks, also reported felt, at 5:15 p.m. and 11:33 p.m. Five small shocks occurred during the night of May 6–7th, one of which was reported felt at Los Nietos. Two other shocks, reported felt at Los Nietos, occurred at 9:29 p.m., on May 17th, and at 4:09 a.m. on May 18th. A few small shocks occurred in the interim between this group and those in July following.

The apparent intensity of the shocks of May 4, 1929, at several places is indicated in Table I. The instrumental data point to an origin near to the source of the shocks in July. This will be discussed later

TABLE I

SHOCKS, MAY 4, 1929

Place	Intensity R-F Scale 5:07 P.M. P.S.T.	5:15 P.M. P.S.T.	11:33 P.M. P.S.T.
Whittier	V+ to VI	felt	V
Whittier (4 miles east)	V	felt	V
Los Nietos	V+	IV	IV
Montebello	V	....	....
Santa Fe Springs	V	felt	....
Clearwater	IV+	....	....
Rivera	IV	felt	....
Norwalk	IV	....	felt
Watson	III	....	....
Brea	felt	....	"strong"
Los Angeles	felt	....	....
Pasadena	felt	....	....
Mount Wilson	felt	....	....
Hermosa Beach	felt (?)	....	....

THE EARTHQUAKE OF JULY 8, 1929

At 8:46 a.m., on July 8th, the strongest earthquake of this series was felt over the area shown on Figure 1 (Plate 18, frontispiece), on which appear isoseismal curves and scattered values of the intensity of the shock. This shock reached barely destructive force within a very small area just to the south and east of the town of Whittier.

As is usually the case, whether because of imperfect information uneven in accuracy or completeness or on account of local peculiarities in the ground, structures, or other conditions, a number of conspicuous anomalies in the manifestation and distribution of intensity were apparent. The outstanding instance is that at Arlington, Riverside County, where an intensity of IV Rossi-Forel, or more, is indicated clearly by the report sent in. This place is one and one-half times as far from the central region as the more distant points otherwise affected by intensity of this grade. In this case no special explanation, such as loose wet ground or unusually susceptible structures, can be offered. All places where intensity IV Rossi-Forel, or higher, was indicated, except Arlington, are inclosed within the broken circle on the map, Figure 1.

Duarte, although situated on ground apparently likely to be shaken strongly, was affected by intensity of grade II Rossi-Forel only, a well-authenticated value, while places all around exhibited intensity of grade V.

Several places south of Lamanda Park, situated on ground of apparently indifferent stability, were affected by intensity of grade II, while effects indicating intensity of IV or V were found in near-by places.

The slightly higher ground in the northwestern part of Whittier showed intensity lower than at other neighboring points.

Covina, built on deep valley alluvium, exhibited effects indicating an intensity of VI Rossi-Forel, in a district otherwise characterized by intensity IV to V.

Owing probably to bad foundation conditions, the Murphy Ranch packing house, situated in the southwestern part of Whittier outside the area of marked structural damage, suffered to some extent.

Owing to much complexity in the nature of the ground at the surface, effects which indicate intensity IV and V Rossi-Forel are intermingled in so tangled a way that it is impracticable to try to draw isoseismal curves demarking the areas characterized by intensity of these grades, or those of still lower value. However, southward along the beach, intensity appeared higher in general than at similar distances from the central region in other directions.

From the isoseismals on Figure 1, it is seen that an elongate area characterized by intensity of grade VII Rossi-Forel extends westward from the vicinity of Norwalk in the direction of Clearwater and Compton. At the latter place the intensity was abnormally high, unstable objects being upset and cracks being developed in the floor of the City Hall. The ground in this vicinity was formerly marshy. Nevertheless the behavior is of interest in connection with the shocks of December 30 and 31, 1928.

Within the area of destructive intensity three buildings, a school house and two residences, were damaged seriously, and a number of others in varying degrees; at Santa Fe Springs flanges on absorption oil towers were broken, two oil wells were plugged by incaving, and a few short, parallel cracks in loose ground were observed. Otherwise the effects were confined to those characteristic of grade VIII Rossi-Forel, such as broken chimneys, disarranged furniture, broken bric-a-brac, and badly cracked and broken plaster.

Aftershocks

During the first twenty-four hours following the main earthquake, no less than one hundred and fifty-five aftershocks were recorded at Pasadena, distant about thirty kilometers from the source; and reports indicate that a large number of these were felt in a small area near and to the south and east of Whittier. Twelve aftershocks were recorded in the fourteen minutes following the main shock prior to 9 a.m. The hour-to-hour record of shock registration for the ensuing thirty hours is shown in Table II. Thereafter these shocks fell off markedly in

TABLE II

Aftershocks on July 8–9, 1929

Hour	No. of Shocks	Hour	No. of Shocks	Hour	No. of Shocks
9–10 a.m.	26	7–8 p.m.	0	5–6 a.m.	0
10–11	17	8–9	5	6–7	0
11–12 a.m.	11	9–10	4	7–8	2
12–1 p.m.	14	10–11	4	8–9	3
1–2	13	11–12 p.m.	4	9–10	2
2–3	12	12–1 a.m.	4	10–11	2
3–4	7	1–2	3	11–12 a.m.	0
4–5	5	2–3	0	12–1 p.m.	1
5–6	5	3–4	2	1–2	0
6–7 p.m.	5	4–5 a.m.	0	2–3	0

frequency of occurrence, only forty-eight being recorded during the remainder of July. However, at irregular intervals since that time shocks have continued to occur in the district, down to the time of writing, and some of these have been recorded at stations, and by means of instruments, which were not in operation in July, 1929. These accordingly have afforded useful supplementary data. One of the most important of these was the shock at 10: 19 a.m. on November 3, 1930.

The following stations have afforded seismometric data for the study of these shocks. First, the stations of the network in Southern California, as follows:

CENTRAL STATION

*Pasadena Seismological Laboratory**
$\phi = 34° \ 08.9'$ N., $\lambda = 118° \ 10.3'$ W., $h = 295$ m., deeply weathered granitic rock with inclusions of gneiss and schist

* Shocks prior to 1927 were registered at Pasadena at experimental stations having different constants, but no use is made here of seismometric data from these.

AUXILIARY STATIONS

Mount Wilson Seismologic Station
$\phi = 34° \ 13.5'$ N., $\lambda = 118° \ 03.4'$ W., $h = 1{,}742$ m., weathered granite

Riverside Seismologic Station
$\phi = 33° \ 59.6'$ N., $\lambda = 117° \ 22.4'$ W., $h = 250$ m. approximately, weathered granite

Santa Barbara Seismologic Station
$\phi = 34° \ 26.6'$ N., $\lambda = 119° \ 42.8'$ W., $h = 100$ m. approximately, heavy boulder-laden alluvium

La Jolla (Scripps Institution Seismologic Station)
$\phi = 32° \ 51.8'$ N., $\lambda = 117° \ 15.2'$ W., $h = 7.7$ m. approximately, consolidated detrital material

Tinemaha Seismologic Station
$\phi = 37° \ 05.7'$ N., $\lambda = 118° \ 15.5'$ W., $h = 1{,}180$ m. approximately, basalt

Haiwee Seismologic Station
$\phi = 36° \ 08.2'$ N., $\lambda = 117° \ 58.6'$ W., $h = 1{,}100$ m. approximately, loosely cemented tuff

The stations at Tinemaha and Haiwee were not put in operation until September, 1929. Consequently no records from these stations are available except for certain aftershocks.

The shock of July 8, 1929, also was recorded at the station of the University of California at Berkeley, at the Branner Seismologic Station at Stanford University, and at the station of the United States

Coast and Geodetic Survey at Tucson, Arizona; and the records from these stations have been available for this study. The station constants follow:

Berkeley (University of California)
$\phi = 37° \ 52' \ 15.9''$ N., $\lambda = 122° \ 15' \ 36.6''$ W., $h = 85.4$ m.

Branner Station (Stanford University)
$\phi = 37° \ 25' \ 03''$ N., $\lambda = 122° \ 10' \ 49''$ W., $h = 82$ m.

Tucson (United States Coast and Geodetic Survey)
$\phi = 32° \ 14.8'$ N., $\lambda = 110° \ 50.1'$ W., $h = 770$ m.

At the present time at all of the stations of the network in Southern California the control and marking of time is accomplished as follows: the minute-marks on the seismograms are co-ordinated directly by means of auxiliary records written at each station, on which the minute-marks are registered in close parallelism with recorded dot-and-dash

TABLE III

DATA OF REGISTRATION

Shock of July 8, 1929

Pasadena	iP_{NE}	8^h 46^m $11^s.7$ a.m., P.S.T.
Mount Wilson	iP_N	12.6
	iP_E	13.0
Riverside	iP_N	17.7
	iP_E	17.5
La Jolla	e_E (= P^*)	29.6
	i_E	30.8
	i_E	31.6
Tucson	$e\overline{P}_N$	48 15
	e_N	23
	e_N	30
	eS_N	56½
	e_N ?	49 08
	eS^*_N ?	12
	e_N	19
	e_N	30
	$e\overline{S}_N$	34
	i_N (?)	8 49 44

radio-telegraphic signals sent in ordinary course from a powerful transmitting station. This permits direct correlation of the minute-marks at all the stations of the group at practically all times with an accuracy of one second, and usually one-fifth second; and sometimes better. This system of time-control was put in operation at Pasadena and Riverside in April, 1929; La Jolla was added on July 1, 1929; Santa Barbara on July 20, 1929; and Tinemaha and Haiwee in September, 1929. This system was not installed at the station on Mount Wilson until November 8, 1930, and therefore was not available in the case of any of the shocks discussed here. However, at Mount Wilson an excellent Riefler clock is used to make the minute-marks on the seismograms, so that dependable time was available for nearly all cases. Further, at the Seismological Laboratory the time-marking clock is compared two to four times daily, by means of time-marks made by automatic relays, with the radio-telegraphic time-signals sent by the United States Naval Observatory from Annapolis, and from Mare Island.

The first motion on the seismograms was a sharp "impulse," to the southeast at Pasadena, to the southward at Mount Wilson, and to the northeast at Riverside. At La Jolla the first motion was a well-defined "emergence" indicating earth-displacement to the northwest, but this was followed by an "impulse" in the opposite direction.

The north-south record at La Jolla was defective through lack of time-marks. The records from Santa Barbara and also from the Branner Station at Stanford University are of relatively little service since the time correction is unknown. The motion on the records from Berkeley is very small, representing chiefly the *S* waves and still later movements, and the data have not been used in this study. At Tucson the east-west component was not available.

For this shock the amplitudes written at the nearer stations were so large that other readings useful for the following discussion could not be obtained. However, the shock was followed by numerous aftershocks of smaller energy. The records of these afford data used in the following discussion. Of course, the origins of these could not have been identical either with that of the main shock, or with each other. On the other hand, they could not have been separated by any considerable distance from each other or from the source of the main shock, since many of them, although very small, were felt distinctly in the region affected by the greatest intensity on the occasion of the main shock. It is, in fact, obvious that these must have originated in the immediate neighborhood of the origin of the main shock.

The more significant data used in the following discussion consist of (1) phase-intervals measured on the seismograms from each of the stations, Pasadena, Mount Wilson, and Riverside; and (2) the time-interval, determined by use of the radio dot-and-dash comparison method, between the arrival of the first motion at Pasadena and its arrival at Riverside, with similar values for other corresponding phases.

On the seismograms written at Pasadena there appear in general, following the first motion, two sharply marked arrivals, here referred to as i_1 and i_2. The former in all probability is $\overline{S}$; the latter appears to be due to the arrival of a reflected wave, as is discussed below. There are other less conspicuous changes in the motion which are not discussed here. At Mount Wilson the later arrival, i_2, is in some instances a little indefinite, while the arrival i_1 is conspicuous in all cases. At Riverside the phase i_2 is usually not easily found, and there is some doubt as to its identification.

The interval, $i_2 - i_1$, in general is more variable than $i_1 - \overline{P}$. At Pasadena $i_2 - i_1$ ranges from 4.0 to 4.6 seconds with a mean value of 4.4. At Mount Wilson $i_2 - i_1$ ranges from 4.1 to 4.5 seconds with a mean value of 4.2. At Riverside the best values for $i_2 - i_1$ are all about 3.4 seconds, but, as stated above, i_2 is difficult to identify on these records.

The following table, Table IV, gives values for $i_1 - \overline{P}$ and for $\overline{P}$ (Riverside) $- \overline{P}$ (Pasadena) for all the cases in which the latter quantity is available. (For convenience also, values of the ratio $V_{\overline{P}}/V_{\overline{S}}$, determined as explained below, are included here.)

TABLE IV

Date	Time (P.S.T.)	$i_1 - \overline{P}$ Pasadena	$i_1 - \overline{P}$ Mount Wilson	$i_1 - \overline{P}$ Riverside	$\overline{P}$ (Riverside) $-$ $\overline{P}$ (Pasadena)	$\frac{V_{\overline{P}}}{V_{\overline{S}}}$
1929						
July 8........	9:20	4.0 sec.	4.7 sec.	7.8 sec.	5.7 sec.	1.67
	9:46	4.0	4.4	7.6	5.3	1.68
	10:09	3.8	4.7±	7.6	5.1	1.74
	11:45	3.8	4.6	8.0	5.6	1.75
	13:35	3.9	4.7	7.9	5.6	1.715
	20:52	4.1	4.3	7.7	5.5	1.655
	20:58	4.2	4.7	7.8	5.4	1.67
July 13........	6:03	3.9	4.6	7.7	5.1	1.745
1930						
Nov. 3........	10:19	4.1	4.7	8.1	5.4	1.74

The best recorded of the aftershocks was that registered on November 3, 1930. For this reason this shock was selected for special study. The complete data for this shock follow.

SHOCK OF NOVEMBER 3, 1930

	$i_1 - \overline{P}$	$i_2 - i_1$	$i_2 - \overline{P}$
Pasadena	$4^s1 \pm 0^s05$	$4^s0 \pm 0^s05$	$8^s1 \pm 0^s05$
Mount Wilson	4.7 ± 0.1	4.2 ± 0.1	8.9 ± 0.1
Riverside	8.1 ± 0.1	3.4 ± 0.1	11.5 ± 0.1

$\overline{P}$ (Riverside) $-\overline{P}$ (Pasadena)	5.4 ± 0.1 sec.
i_1 (Riverside) $- i_1$ (Pasadena)	9.4 ± 0.1 sec.
i_2 (Riverside) $- i_2$ (Pasadena)	8.8 ± 0.1 sec.

(The plus-or-minus (±) corrections shown indicate the *limits* of error—*not* the probable error.)

Because of its questionable identification no emphasis is placed upon values of i_2 determined at Riverside.

The area which includes the stations Pasadena, Mount Wilson, and Riverside (and even La Jolla and Santa Barbara) is so small that, unless a shock originates at very considerable depth, no error of consequence can result if rectilinear propagation of the wave motion with uniform velocity is assumed. It is certain, of course, that some increase in velocity must occur as the depth of the wave-path increases, but this increment is so small that it may be neglected except in cases where the path traverses long distances at great depth.

Now in the case of the main shock the very small area affected by intensity of the higher grades points to an origin at small depth; and this is supported to a certain extent by the registration at Pasadena, only about thirty kilometers from the central region, of surface waves with amplitudes conspicuously greater than is usual in otherwise similar shocks and with periods as long as five seconds. Also it may be noticed in this connection that a rolling motion following the sharp jolt of the main shock was reported from a number of places in and near the region of highest intensity. Observations of such action are not usual.

The hypocenters of the aftershocks cannot have differed significantly from that of the principal earthquake and this is supported by the fact that no large differences are found in the measured phase-intervals for the numerous aftershocks as registered at Pasadena, Mount Wilson, and Riverside.

After an exhaustive study of these shocks it has been found possible to obtain satisfactory solutions for the epicenters, focal depths, and wave-velocities only on the most natural assumptions: (1) that the first motion recorded at Pasadena, Mount Wilson, and Riverside corresponds to the arrival of $\overline{P}$ (the longitudinal wave which travels along the direct path from hypocenter to station—in actuality probably a slightly curved path but one here assumed to be rectilinear); and (2) that i_2 is S (the corresponding transversal wave).

Many hypotheses different from this were considered but all were found either obviously wrong or in less good agreement with the data than this simplest one. These are discussed farther on.

On this hypothesis the data for $i_1 - \bar{P} = \bar{S} - \bar{P}$ at Pasadena and Riverside, together with $\bar{P}$ (Riverside) $- \bar{P}$ (Pasadena), yield values for the ratio of the velocities $V_{\bar{P}}/V_{\bar{S}}$ according to the formula

$$\frac{V_{\bar{P}}}{V_{\bar{S}}} = \frac{\bar{S}\text{ (Riverside)} - \bar{S}\text{ (Pasadena)}}{\bar{P}\text{ (Riverside)} - \bar{P}\text{ (Pasadena)}}$$

These values have been given in Table IV, for the shocks listed in that table, which includes all for which this computation can be made. The mean of these is 1.702+ which is close to the value 1.713 derived from study of blasts in this region.[1]

It is to be noted that the variations in $V_{\bar{P}}/V_{\bar{S}}$ as thus determined must be statistical in character since the velocities can hardly differ significantly over the very slightly varying paths traversed in these cases. The values for $V_{\bar{P}}/V_{\bar{S}}$ therefore may be treated as so many observations of the same quantity. Considering the possible errors of measurement, which in general are about the same as those given already in the case of the shock of November 3, 1930, the observations are seen to be consistent with a value of about 1.71. Accordingly this value was adopted as an additional datum in investigating these shocks.

Now, in the course of this study a great many trials were made, both approximate by means of graphical methods and, for greater accuracy, by calculation, to find solutions in accord with the data of the shock of November 3, 1930, and of others of the aftershocks as well. In this exploratory investigation the limits of the data were used as well as the direct readings. Mean and "normal" values also were tried out. Using the widest or "inclusive" limits of the data of measurement, small, but nevertheless too large, surface areas and sub-surface volumes were delimited by the intersections of the several spherical and hyperboloidal surfaces thus determined, within which the focus, or foci, of shock could be located. Using somewhat narrower limits,

[1] H. O. Wood and C. F. Richter, "A Study of Blasting Recorded in Southern California," *Bulletin of the Seismological Society of America,* 21, 28, March, 1931.

however, much smaller surface areas and sub-surface volumes were thus marked out. Important limitations were found to be imposed by the necessity of accounting, reasonably and consistently, for the occurrence of the phase i_2.

Thus, by successive approximations, after many trials the solution arrived at which proved to be in best agreement with all the data for the shock of November 3, 1930, was found to be the point determined by $\phi = 33° 54.9'$ N., $\lambda = 118° 01.9'$ W., at depth $= h = 13.1$ kilometers (8+ miles). The corresponding velocities arrived at are $V_{\overline{P}} = 5.55$ kilometers per second and $V_{\overline{S}} = 3.25$ kilometers per second. The epicenter thus determined is shown on the map (Fig. 2).

The conclusion thus reached is consistent with study of the phase i_2 which appears on the records at Pasadena and Mount Wilson, and probably, though uncertainly, at Riverside. The seismometric data given already are sufficient to locate the region of origin about eight kilometers south of Whittier, and this is consistent with the evidence from the field data. Extended consideration of the phase i_2, and the trial of many hypotheses as to its nature and cause, led to the conclusion, again and again, that this phase represents the arrival of a reflected S-wave at the stations mentioned. Detailed numerical investigation at length fixed the origin and velocities given above, and in addition indicated, consistently, the depth of the reflection at about twenty-four kilometers.

It is worth notice that the simple reflection of $\overline{P}$ at about this same depth, twenty-four kilometers, was found to afford one of two explanations for an unexpected phase-arrival observed on the records of certain blasts set off in this region.[2]

The amplitudes of i_2 are large at Pasadena and Mount Wilson, indicating that the intensity of the waves supposed to be reflected is marked, and this legitimately may raise a question as to the correctness of this interpretation. For it appears that the reflection in question must take place at an angle of incidence of about 40 degrees (for Pasadena and Mount Wilson). If this hypothetical reflection at a depth of twenty-four kilometers takes place at the supposed discontinuity between granitic and basaltic, or basic, material, 40 degrees is almost certainly less (steeper) than the critical angle, and a low coefficient of reflection might be expected. Nevertheless, a reflected transversal wave of high intensity is possible at or near the angle for

[2] H. O. Wood and C. F. Richter, *op. cit.*

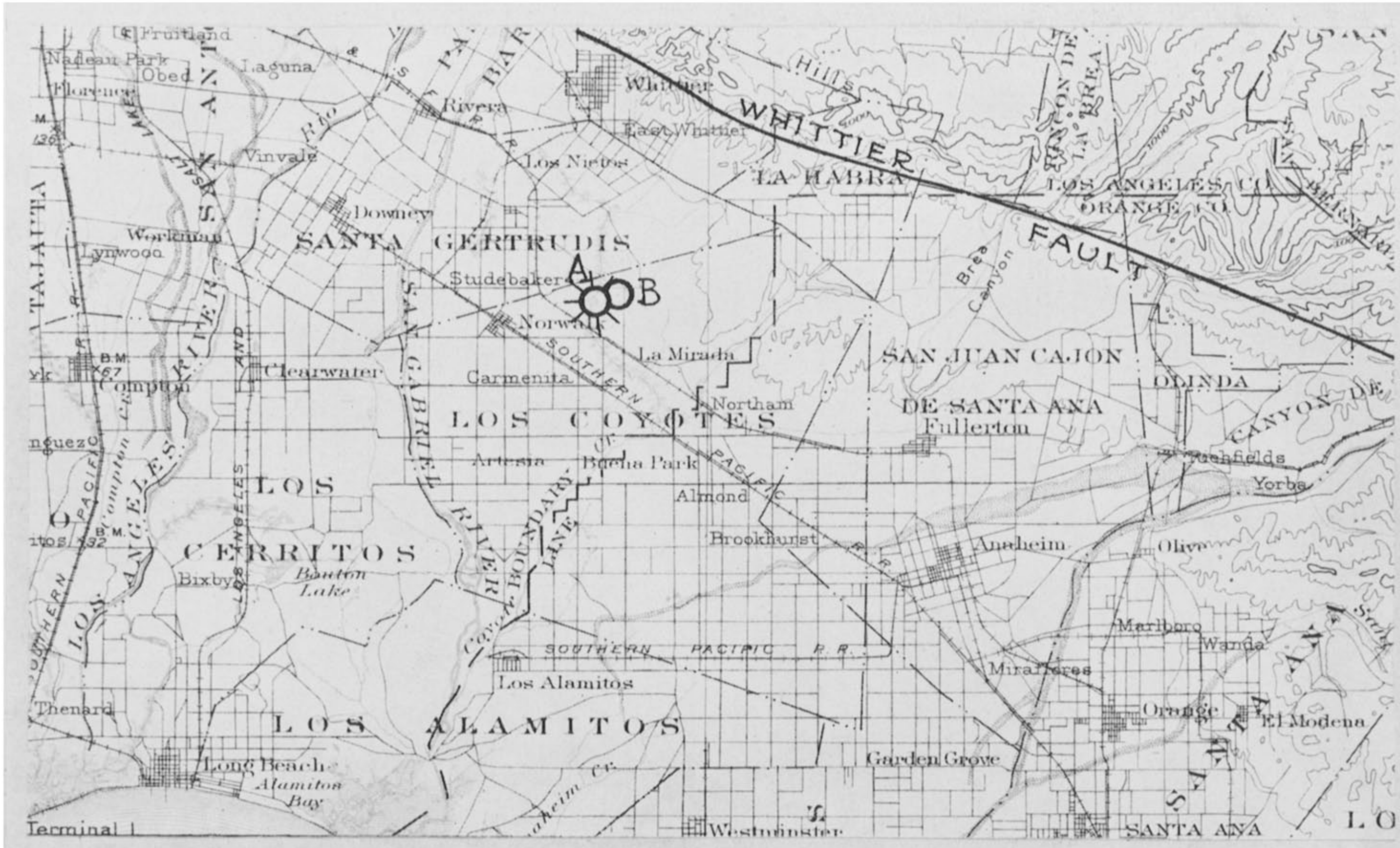

FIG. 2. *A* is epicenter adopted for chief shock of July 8, 1919; *B* is epicenter of shock of November 3, 1930

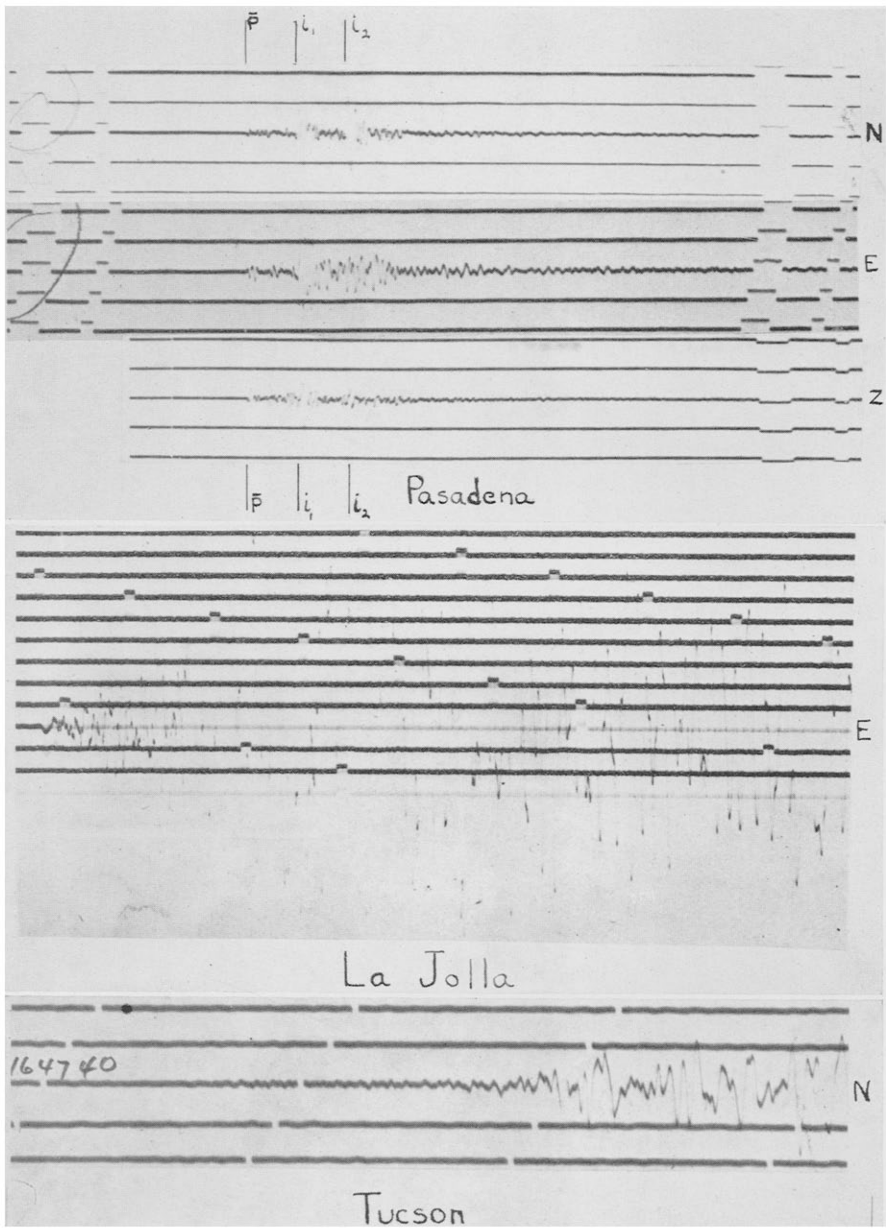

FIG. 3.—Pasadena records of November 3, 1930, shock; La Jolla and Tucson records of chief shock of July 8, 1929.

which the derived longitudinal wave in the lower medium grazes the discontinuity, provided that the densities and elastic constants satisfy approximately certain relations. This latter angle of incidence is considerably less (steeper) than the critical angle for ordinary reflection, and with reasonable assumptions as to the velocities may be near 40 degrees. It follows that the explanation of i_2 here offered, namely $\bar{S}_{24}\dot{S}$, though subject to question as mentioned above, is by no means excluded a priori, while it fits the arrival times reasonably well. (See the diagram, Fig. 4.) Further, it is to be noted that this phase, i_2, at Pasadena appears to be strongly polarized; the impulse is conspicuous on the seismograms for the north-south and vertical components, but it is found much less easily on that for the east-west component. (See Fig. 3.) Such polarization naturally suggests reflection. No other reasonable explanation for this phase has been found, notwithstanding thorough investigation.

Other Shocks

Similar solutions have been found satisfactory for other shocks of the series, besides that of November 3, 1930, and these lead to epicenters in the immediate neighborhood of the one specified above, to depths of focus of the same general value, and to practically the same values for the velocities.

Consequently an epicentral point has been settled upon which best represents the data for a majority of the aftershocks of July 8th and those following soon after, which therefore probably is very close to that of the main shock. Using this epicenter and a value for the depth near those found most frequently for these aftershocks, the following solution has been worked out and adopted as the closest approximation obtainable in the case of the main shock of July 8, 1929: $\phi = 33° \; 54'.8$ N., $\lambda = 118° \; 02'.4$ W., depth $= h = 13$ kilometers (8+ miles). On this basis the origin time was $O = 8^h46^m07^s$ a.m. P.S.T. $= 16^h46^m07^s$ G.C.T. This epicenter also is indicated on the map (Fig. 2). As the outcome of thorough study of all available data, we have become confident that the epicenter of the main shock could not have been distant more than three kilometers (1.9 miles) from this point, and with great probability it was much nearer. The depth fixed upon, thirteen kilometers (8+ miles), appears consistent with the shallow origin indicated by the field data. Should the true epicenter be as much as three kilometers (1.9 miles) to the north of the point fixed upon (it can hardly be located more than one kilometer [0.6 mile] to the south), the depth of focus would have to be considerably greater than thirteen kilometers—and this does not appear plausible.

Transmission-Time Diagram

Arrival-time data are shown on Figure 4, the well-known type of transmission-time diagram, on which the times of arrival of the various phases indicated on the seismograms at the stations named are plotted against the distances of these stations from the above-mentioned epicenter determined by calculation, as follows:

	Δ Kilometers	Δ Miles
Pasadena	28.7	17.9
Mount Wilson	34.65	21.5
Riverside	62.1	38.5—
La Jolla	136.8	85—
Santa Barbara	163	101
Haiwee	247	153
Tinemaha	354	220—
Stanford	541	335
Tucson	695	432

On this diagram solid circles mark the data of the main shock as given above. Open circles mark additional points derived from measurement of the aftershocks; and these points correspond to the following:

a) *Mean data of aftershocks, July 8–10, 1929*

	Pasadena	Mount Wilson	Riverside
$\bar{S}-\bar{P}$	$4^s.0$	$4^s.7$	$7^s.7$
$i_2-\bar{S}$	4.4	4.2	3.4

b) *Shock of November 24, 1929, at 22^h00^m P.S.T.*

e_1 (Santa Barbara) $-\bar{P}$ (Pasadena)	23 seconds
e_2 (Santa Barbara) $-\bar{P}$ (Pasadena)	42 seconds
e_1 (Haiwee) $-\bar{P}$ (Pasadena)	39 seconds
e_2 (Haiwee) $-\bar{P}$ (Pasadena)	65 seconds

c) *Shock of November 3, 1930, at 10^h 19^m P.S.T.*

e_1 (Santa Barbara) $-\bar{P}$ (Pasadena)	26 seconds
e_2 (Santa Barbara) $-\bar{P}$ (Pasadena)	43 seconds
e_1 (Tinemaha) $-\bar{P}$ (Pasadena)	62 seconds
e_2 (Tinemaha) $-\bar{P}$ (Pasadena)	97 seconds

The construction of transmission-time curves by aligning the open circles with the solid circles obviously involves the assumption, which is true only approximately though closely, that the sources of the shocks

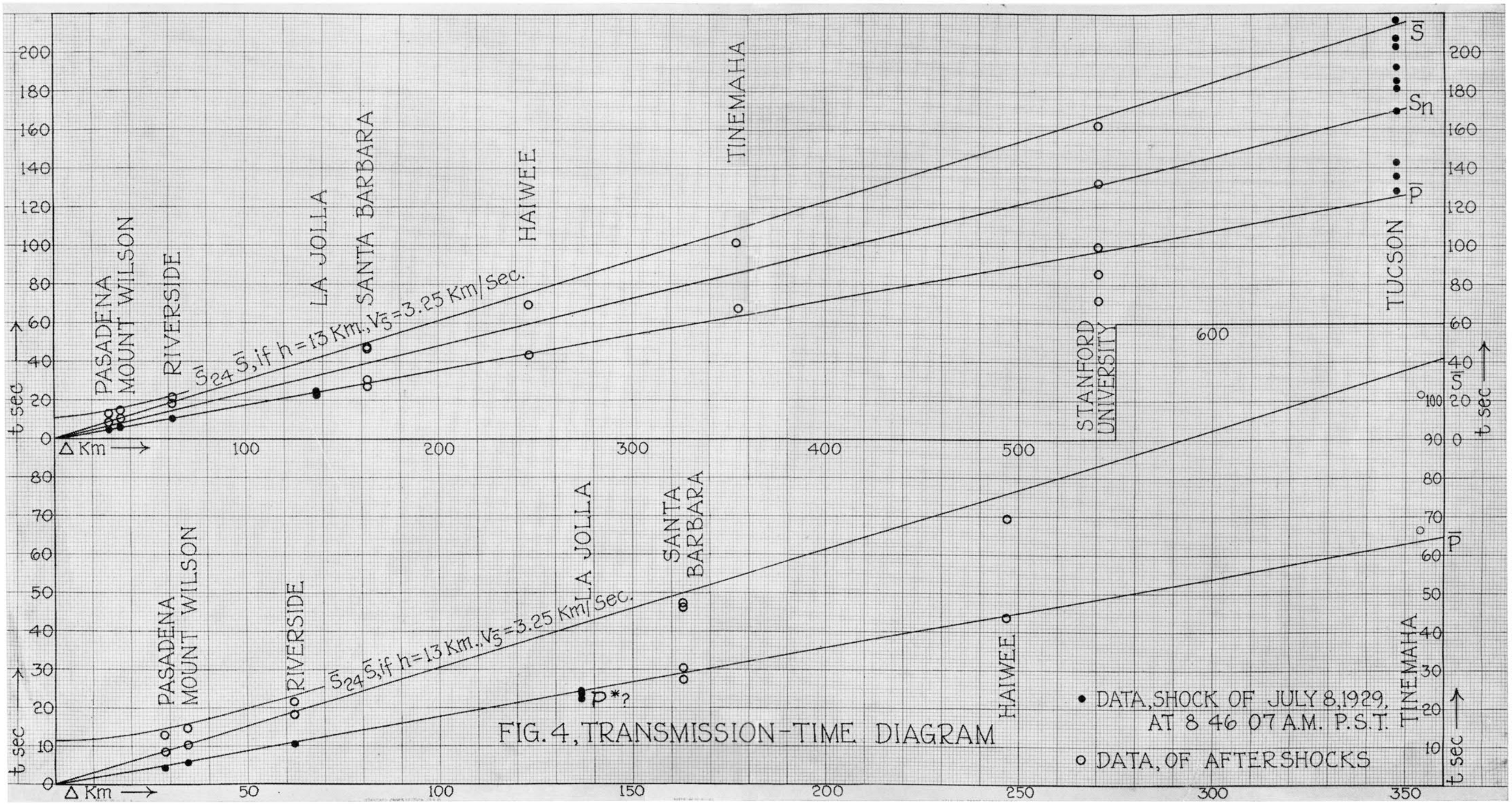
FIG. 4, TRANSMISSION-TIME DIAGRAM
• DATA, SHOCK OF JULY 8, 1929, AT 8 46 07 A.M. P.S.T.
○ DATA, OF AFTERSHOCKS
$\bar{S}_{24}\bar{S}$, if h=13 Km, $V_{\bar{S}}$=3.25 Km/Sec.
PASADENA
MOUNT WILSON
RIVERSIDE
LA JOLLA
SANTA BARBARA
HAIWEE
TINEMAHA
STANFORD UNIVERSITY
TUCSON
$\bar{S}$
Sn
$\bar{P}$
P*?
t sec
Δ Km

Fig. 4

under (*b*) and (*c*) do not differ from the main shock. However, at stations more distant than Riverside the times indicated by the open circles represent phases marked by motion of small amplitude and indefinite emergence.

At the Branner Station at Stanford University no clock correction was available. However, the first phase noticeable on the seismograms from this station is identified tentatively as Pn. There follow four reasonably well-indicated phases at 13.8, 28, 60.4, and 90 seconds after the beginning of motion. If the third of these is identified as $\overline{P}$, the fourth and fifth then fit the curves for Sn and $\overline{S}$ very well.

Further it appears probable that the first arrival at La Jolla and the second arrival at the Branner Station at Stanford are P^*, which identification indicates a velocity of 6.5 kilometers per second for this.

In addition there is shown on this diagram a curve calculated for the arrival-times of the phase $\overline{S}_{24}\overline{S}$, assuming $h = 13$ kilometers, and $V_{\overline{S}} = 3.25$ kilometers per second. In comparing this curve with the measured arrival-times of i_2 at Pasadena, Mount Wilson, and Riverside, allowance must be made for the fact that Mount Wilson stands one and one-half kilometers (0.9 mile) above the level of the sea, taken as the reference plane, so that i_2 ought to arrive there a fraction of a second later than the time indicated by the curve.

Alternative Phase Interpretations

Before finally adopting the solutions presented above, extended consideration was given to possible alternative interpretations for the phases P, i_1, and i_2. In view of the complications which have been found by other workers in the study of very near shocks, it is clear that the simplest interpretations for $\overline{P}$ and i_1, as the direct longitudinal and transversal waves, respectively, might perhaps be incorrect. Accordingly attempts were made to explain the data on the basis of several of the alternatives thus suggested. It is obvious that any explanation must account for all of the three conspicuous phases on a consistent basis. After many trials the conclusion was reached that the simple hypothesis is the only one which is in close agreement with all the data. The more important alternative cases are discussed immediately below.

1. The hypothesis has been advanced[3] that in near shocks the longitudinal wave may originate, not at the hypocenter but on the arrival

[3] Jeffreys, Harold, "On Two British Earthquakes," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement,* **1**, 486, 1927.

of the transversal wave at the base of the sedimentary layer (or possibly at the surface), the part of the path traversed as a longitudinal wave being practically horizontal. If this holds for the shocks studied here, the difference between the epicentral distances of Riverside and Pasadena, Δ (Riverside) $-\Delta$ (Pasadena), must be equal to the difference between the arrival-times of the first motion at these stations, $\overline{P}$ (Riverside) $-\overline{P}$ (Pasadena), multiplied by the velocity of the longitudinal waves along horizontal paths near the surface. From a study of blasts in this region[4] this velocity has been found to be about 5.5 kilometers per second.

For the shock of November 3, 1930, the first motion at Riverside was registered 5.4 seconds later than at Pasadena. Δ (Riverside) $-$ Δ (Pasadena) should be, therefore, about 29.7 kilometers (18.4 miles). Since, under this hypothesis, $\overline{S}$ is considered to travel along the direct path from source to station, an analogous multiplication should yield the difference in hypocentral distance between the two stations, D (Riverside) $- D$ (Pasadena). Now i_1 was registered 9.4 seconds later at Riverside than at Pasadena. If i_1 is identified as $\overline{S}$, and its velocity is taken as 3.3 kilometers per second, D (Riverside) $- D$ (Pasadena) is 31.0 kilometers (19.2 miles). This distance is greater than the va'ue just found for Δ (Riverside) $-\Delta$ (Pasadena). Such a result is a manifest geometrical impossibility, for though D (Riverside) $> \Delta$ (Riverside) and D (Pasadena) $> \Delta$ (Pasadena), necessarily it must be that D (Riverside) $- D$ (Pasadena) $< \Delta$ (Riverside) $- \Delta$ (Pasadena). The numerical data just used have been given their most probable values. By taking extreme values, we can find

Δ (Riverside) $-\Delta$ (Pasadena)	5.5 sec. $\times$ 5.55 km/sec.	30.6 km (19.0 miles)
D (Riverside) $- D$ (Pasadena)	9.3 sec. $\times$ 3.2 km/sec.	29.7 km (18.4 miles)

These latter results are consistent geometrically with this hypothesis, but by a very small margin only. Moreover, the source indicated by such values is too shallow and too far to the north to be consistent with other data, and as even this barely consistent result depends on extreme values for the data, it is clear that this hypothesis does not afford a satisfactory explanation for these observations.

A similar difficulty is encountered if i_2 is identified as $\overline{S}$.

2. An entirely different hypothesis[5] is that $\overline{P}$ is the arrival of the

[4] H. O. Wood and C. F. Richter, *op. cit.*

[5] "Das Rheinlandbeben vom 13 Dezember, 1928," *Gerlands Beiträge zur Geophysik,* **23,** 22, 1929.

direct longitudinal wave from source to station, and i_2 that of the similar direct transversal wave $\bar{S}$, while i_1 is a wave which originates at the surface on the arrival there of the longitudinal wave, and then travels horizontally with the velocity of a transversal wave. If we write

$$\gamma = \frac{i_1 - \bar{P}}{\bar{S} - \bar{P}}$$

then if h is the depth of focus, V_P the velocity of the longitudinal wave, and V_S the velocity of the transversal wave, this hypothesis gives

$$\frac{h}{\Delta} = \sqrt{\frac{1}{[V_S/V_P\,(1-\gamma)+\gamma]^2} - 1}$$

For the shock of November 3, 1930, as registered at Pasadena, $\gamma = \frac{4.1}{8.1} = 0.506$. Taking $V_S/V_P = 0.56$ we obtain $h/\Delta = 0.8$.

Now $\frac{D}{\bar{S}-\bar{P}}$ $(=k)$ can hardly be less than seven; and on this present hypothesis $\bar{S}-\bar{P}$ would be 8.1 seconds. Hence D would be at least 56 kilometers (34.7 miles). From this result and the ratio $h/\Delta = 0.8$, a minimum value of Δ can be computed, namely, $\Delta_{\min} = 44$ kilometers (27.3 miles). A more reasonable value for k would increase this figure considerably. But even this value, $\Delta = 44$ kilometers (27.3 miles) at Pasadena, is far too large to accord with either the data of field observations or the remaining seismometric readings. Moreover, small changes in the value of γ, or of V_S/V_P, or both, do not affect this conclusion materially. Therefore, this hypothesis also fails to account satisfactorily for the observations at hand.

The region strongly affected by the shock in July, 1929, is practically the same as that disturbed by the shocks of May 4, 1929. The $\bar{S}-\bar{P}$ intervals of these shocks differ only slightly from those of the July shocks. The origins, therefore, probably are displaced only slightly from those of the main group.

Returning now to a consideration of the shocks of December 30 and 31, 1928, it is to be noted that the $\bar{S}-\bar{P}$ intervals indicate an origin slightly nearer to Pasadena, approximately the same distance from Mount Wilson, and somewhat farther from Riverside, than those of the shocks considered above. Such an epicenter would be located a little to the west of these in the direction of Compton. The shocks of this group, especially the stronger one, exhibited marked intensity at

Compton. It has been mentioned previously that abnormal intensity was reported from the vicinity of Compton at the time of the July 8, 1929, shock. It is to be noted that the phase i_2, conspicuous on the seismograms of the shocks studied above, is not to be found on the records of this group of shocks. This circumstance makes it necessary to regard the interpretations of i_2 as $\overline{S}_{24}\overleftarrow{S}$ with caution.

GEOLOGICAL NOTES

With little doubt all the shocks referred to in this paper originated beneath an area, say thirty kilometers in radius, roughly centered some ten kilometers south of Whittier. Further, all the epicenters of the group studied intensively here were located within a very small area, say five kilometers or less in radius, about this center. Immediately to the north and east, both of the larger and the smaller region of origin, rise the Puente Hills, carved from an uplifted and tilted body of sediments of Tertiary (Miocene and Pliocene) age. Along and through the south and southwest flanks of these hills trends the Whittier fault, a well-known and marked dislocation which merges at the east with the Elsinore fault zone, while to the west it is not known to extend beyond the termination of the Puente Hills. Numerous field observations on the surface show that this fault dips steeply to the north by different amounts in different places, and in at least one place this is confirmed by findings at considerable depth where an oil well which starts at the surface in rocks outcropping to the north of the fault trace passes down through these and through the broken fault zone into the rock series found at the surface south of the fault outcrop. This is an important finding since it indicates that this fault does not dip to the south unless reversal of dip takes place at very considerable depth.

Because the Whittier fault is a feature which exhibits marked expression in the topography it was at first considered probable that a slipping at depth upon this fault was the cause of these shocks. Consequently diligent efforts were made to find solutions, consistent with the instrumental and field data, which would locate the origin upon this fault. These efforts were fruitless. Only by extreme and unreasonable assumptions could epicenters be located as far north as the surface trace of this fault; and for moderate depths of origin, in view of the dip found, epicenters still farther north would be necessary. However, for such epicenters, unreasonably great depths were indicated by the instrumental data. All consistent solutions, harmonious also with the field observations, indicate origins at depth of about thirteen kilometers (8+ miles) well to the south of the Whittier fault. Whether the origin is on a branch fault which joins with this conspicuous zone can only be conjectured.

To the south of the Puente Hills, and the Whittier fault, is a small area of low rolling hills with intervening small, marshy streams of low gradient and uncertain wandering courses. These hills terminate at the south somewhat irregularly, but nevertheless rather abruptly, against the flat expanse of the Los Angeles plain. The smaller, more restricted, epicentral area is located near the southwest margin of these low rolling hills. Directly beneath this area, and much of the district immediately surrounding it, is a cover of alluvium of considerable but greatly varying depth which in many places is marshy in the wet season. (Its effect upon the surface intensity was notably variable.) Beneath this is a great thickness of Tertiary sediments, largely shales, but with sandstones interbedded, and also other materials in very subordinate amount. This rock series extends to great depth. It has been penetrated by drilling to a depth of about three kilometers (about 10,000 feet) without reaching the crystalline basement upon which, supposedly, it was laid down. How much deeper these sediments extend can only be conjectured. There is no reason to doubt, however, that beneath them is the granitic complex elsewhere found at the base of similar formations, which complex in still other places forms the surface over extended areas, and in comparatively near mountain summits reaches heights in excess of three kilometers above sea-level. The remarkable irregularity in the present surface of this crystalline complex is thus manifest.

Notwithstanding the unusually deep sedimentary body, or "layer," immediately beneath the epicentral tract of these shocks, the seismograms written at Pasadena, Mount Wilson, and Riverside (as well as at more distant points) do not seem to present peculiar features which may be ascribed to this condition. The rock at the surface underneath these three stations is the crystalline granitic rock of the basement complex and, unless the sediments referred to above are very much deeper, even, than is known or conjectured, the direct wave-paths from hypocenter to station in all three cases pass through the crystalline material without encountering the sediments. It is possible, however, that these rectilinear wave-paths may encounter sedimentary material for a short distance beneath the district just south of Pasadena.

Also efforts were made, but wholly without success, to explain the phases i_1 and i_2 as due, perhaps, to reflection, refraction, or modification of the wave motion where it encountered the base of this sedimentary body, since some action of this kind might reasonably be expected. However, any phases which may be due to the arrival of motion after such modification must be of small amplitude and uncertain onset, for none such have been recognized.

As always, the effects observable in the field were affected by the surface geological conditions. In the area in which these shocks were felt, extending to a distance of seventy-five kilometers (46.5 miles) more or less, from the center are found the weathered surfaces of the crystalline basement complex, in the Sierra Madre with its high summits, its steep slopes, and deep canyons, in the outlying Verdugo Mountains and the San Rafael Hills, the similar but more gently modeled surface of the Perris plain (with its higher upland to the northwest)—the San Jose and Puente Hills cut from Tertiary sediments, the bolder and more complex mass of the Santa Ana Mountains, the low San Pedro Hills, and the complex body of the Santa Monica Mountains. Contrasted are the deeply alluviated Los Angeles plain with deep underlying sediments, and the deep basins of alluvium known as the San Fernando Valley, the San Gabriel Valley (with adjoining smaller basins), and the Cucamonga Valley. Strictly speaking these basins are depressed crust blocks laden with sediments, alluvium, and recent piedmont outwash. This great variety in the nature and thickness of the geological materials at the surface is reflected in the complexity of the effects of shock observed in the field. When the heterogeneous nature of the structures, and other intensity indicators, is also taken into account, it is not a cause for surprise that it is impossible, practically speaking to draw well-determined isoseismal curves except in the immediate neighborhood of the epicenter.

Summary

1. A list of shocks which have occurred near Whittier, California, in recent years is given, with brief discussion. Field data are given in tabular form for the shocks of May 4, 1929; and on a map showing values of intensity for the shock of July 8, 1929, at $8^h\ 46^m\ 07^s$ a.m., P.S.T. Aftershocks are discussed briefly.

2. The data of registration for the main shock and for several aftershocks, especially that of November 3, 1930, are given. Phases

registered were identified as $\overline{P}$ and $\overline{S}$, and rectilinear propagation of the wave motion assumed. Without further assumption a value of the ratio of velocities $V_{\overline{P}}/V_{\overline{S}}$ was determined.

3. A solution for the epicenter and depth of focus of the shock of November 3, 1930, at 10:19 a.m., was determined as follows: $\phi = 33° 54.9'$ N., $\lambda = 118° 01.9'$ W., depth $= h = 13.1$ kilometers (8+ miles), with corresponding velocities $V_{\overline{P}} = 5.55$ kilometers per second, $V_{\overline{S}} = 3.25$ kilometers per second.

4. A third conspicuous phase was identified on the seismograms as $\overline{S}_{24}\overline{S}$, a transversal wave reflected at a depth of about 24 kilometers (15— miles).

5. On the basis of aftershock data, together with data for the main shock, an epicenter and depth of focus for the latter was approximated, and a corresponding origin-time adopted, as follows:

$\phi = 33° 54.8'$ N., $\lambda = 118° 02.4'$ W., depth $= h = 13$ kilometers (8+ miles), and

$O = 8^h 46^m 07^s$ a.m., P.S.T. $= 16^h 46^m 07^s$ G.C.T., July 8, 1929

6. A transmission-time diagram is given on the basis of the data of the main shock, together with that of certain aftershocks.

7. Alternative interpretations of the phases identified as $\overline{P}$, $\overline{S}$, and $\overline{S}_{24}\overline{S}$ are discussed.

8. The geological conditions and the probable nature of the material traversed by the waves is discussed.

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